# SOLAR CROP DRYING

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## ABSTRACT

Crop drying is a necessary step in the food production system. Without adequate drying, a crop would be quickly lost to mould infestations. This paper examines first, the drying requirements, then the different aspects of design, construction, operation, and maintenance of solar dryers. Examples of different research projects on drying are used as illustrations.

## KEYWORDS

Solar; drying; crops; moisture.

## INTRODUCTION

"The massive research efforts of the past few decades aimed at increasing food production in the developing countries, particularly production of cereal grains, have been quite successful. Scientists have developed new varieties of crops that provide higher yields, need shorter growing seasons, and are to some extent more resistant to drought, pests, and diseases. Their acceptance by farmers in developing countries in many cases has been very good. Improved cropping practices, such as multiple cropping, intercropping and new crop rotation techniques have also added greatly to the crop yields." (Forrest and colleagues, 1980)

However, in many instances the positive gains of these developments in crop production have been negated by the inadequacy of existing post-production systems (PPS) to handle more grain and at different times. Losses in weight, quality, nutrition, viability, and economic losses all take their toll.

These losses come about partially through the rejection of traditional post-production systems which, although having low productivity, were successful in many other respects. The traditional grain varieties were often loose-panicled types (therefore they could dry on the head) which matured at the end of the rainy season They were harvested dry and threshed at a time when the farmer and his family had adequate time to carry out the work. The newly developed varieties have shorter maturing periods enabling the farmer to get two harvests annually. They are mainly ~~of the~~ closed panicle types and the second harvest often falls within the rainy season. This presents a number of problems since the harvest comes when the farmer often does not have either the facilities or manpower to adequately dry his crop. Also, as is the case with sorghum and millet, the closed panicle requires a longer drying period. Under tropical conditions during the rainy season grain must be reduced from the 20-30 per cent moisture content at which it is often harvested to 15 per cent or less within a day or two if the grain is to be saved from microbiological and biochemical decay.

## WHY DRY CROPS?

### Maxiumum Moisture Content Allowed in Crops

Different

The moisture content (m.c.) of the grain establishes a relative humidity (r.h.) in the air surrounding the individual seeds which may support the growth of ~~fungi, and~~ moulds, each having a minimum r.h. below which they cannot survive. Generally this minimum r.h. is 65-70 per cent and corresponds to the following grain moisture content levels at 27°C. (Hall, 1970)

TABLE 1 Maximum Allowable m.c. for Safe Storage

| Grain | m.c. level | Grain | m.c. level |
|---|---|---|---|
| Maize | 13.5 | Wheat | 13.5 |
| Sorghum | 13.5 | Millet | 16.0 |
| Paddy | 15.0 | Rice | 13.0 |
| Cowpeas | 15.0 | Shelled groundnuts | 7.0 |
| Beans | 15.0 | | |

### Moulds and Weight Loss

Excessive grain m.c. has an effect on respiration rates of moulds. As can be seen from Table 2, mould-infested grain has a higher respiration rate, and since production of 14.7 g of $CO_2$ is accompanied by a 1 per cent dry matter loss, presence of moulds, increase in grain m.c., and increase of grain temperature can all lead to weight loss.

TABLE 2 Mean Respiration Rates of Stored Mould-Infected and Mould-Free Wheat (Kreyger, 1972)

| Moisture Content per cent Wet Basis | Respiration Rates: mg $CO_2$ per 24 hours per 100 g dry matter | |
|---|---|---|
| | Mould-Infected Wheat (35°C) | Mould-Free Wheat (35°C) |
| 14.9 | 2 | 1 |
| 16.0 | 23 | 1 |
| 18.0 | 56 | 6 |
| 20.2 | 1404 | 55 |
| 24.2 | 1694* | 179 |
| 27.7 | 1639* | 549 |
| 30.8 | 1608* | 265 |

*Figure not higher because of lack of oxygen. Apart from deterioration due to mould growth, a high respiration rate due to moulds must be an indication of a breakdown of dry matter in the grain.

In the process of respiration there is a liberation of heat and water

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + 677.2 \text{ cal} \qquad (1)$$

An increase in respiration rate therefore increases grain m.c. and grain temperature which in turn speed up the reaction. This situation can lead to grain rotting. As the number of moulds increases, they increase the grain moisture content and temperature. Since grain has a low thermal diffusivity, the generated heat is contained within a small volume. Increased heat and moisture content in turn lead to increased mould growth and respiration. This process continues until we have total rotting of the grain. This condition is often called a "fungal hot ~~sport~~". spot" (Sinha, 1971)

## Moulds and Seed Viability

Moulds not only increase the respiration rate and therefore reduce the amount of dry matter, they also lead to a loss in seed viability. Loss in seed viability is often used as the main index of storage sutiability, and is certainly important to the farmer who used his own seed for next year's planting. It is also important to consumers in processes such as brewing.

Taylor (1975) gives the following rules concerning grain temperatures and moisture content:

1. For seeds between 5 and 14 per cent moisture content the length of time in storage before seed viability significantly declines is doubled for every 1 per cent reduction in seed moisture content.
2. For every 5 degree C reduction in storage temperature, the length of time in storage before seed viability declines significantly is doubled.

## Moisture Content and Insects

Every biological species has an optimum temperature range. In general, tropical insects do not survive temperatures below $20^oC$ or above $45^oC$. Temperate zone species are unable to reproduce below $10^oC$. Tolerance to extremes in temperature depend on previous grain history. A sharp rise in temperature above $40^oC$ or a sharp decline in temperature below $10^oC$ may be adequate to kill an insect population in a grain store. Even at optimum temperatures the insects still require a certain moisture content level and extremely dry grain is not favoured by insects irrespective of temperature. This is one more reason why drying is necessary.

Inadequate drying therefore results in losses from the following sources:

1. Losses in weight due to insects being able to reproduce and due to respiration
2. Losses in germination--due to moulds and insect damage
3. Losses in quality and nutritional value--due to combinations of moisture, temperature, and presence of moulds
4. Economic losses--due to all of the above.

## Overdrying

Economic loss can also be caused by overdrying. From Table 3 one notes that a kg of grain at 15 per cent when dried to 4 per cent weighs only 885.4 g. Unless the grading system takes this into account the farmers will suffer a loss.

TABLE 3 Change in Weight in 1 kg of Grain due to Drying

| Final m.c. | Initial m.c. | | | | | |
|---|---|---|---|---|---|---|
| | 5% | 7% | 9% | 11% | 13% | 15% |
| 4% | 0.9896 | 0.9687 | 0.9479 | 0.9271 | 0.9063 | 0.8854 |
| 5% | 1.0000 | 0.9789 | 0.9579 | 0.9368 | 0.9158 | 0.8947 |
| 6% | 1.0106 | 0.9804 | 0.9681 | 0.9468 | 0.9255 | 0.9043 |
| 7% | 1.0215 | 1.0000 | 0.9789 | 0.9570 | 0.9355 | 0.9140 |
| 8% | 1.0330 | 1.0109 | 0.9891 | 0.9674 | 0.9457 | 0.9239 |
| 9% | 1.0440 | 1.0220 | 1.0000 | 0.9780 | 0.9560 | 0.9341 |
| 10% | 1.0556 | 1.0333 | 1.0111 | 0.9889 | 0.9667 | 0.9441 |
| 11% | 1.0674 | 1.0449 | 1.0225 | 1.0000 | 0.9775 | 0.9551 |
| 12% | 1.0795 | 1.0568 | 1.0340 | 1.0115 | 0.9773 | 0.9659 |
| 13% | 1.0920 | 1.0690 | 1.0460 | 1.0230 | 1.0000 | 0.9770 |
| 14% | 1.1047 | 1.0814 | 1.0581 | 1.0349 | 1.0116 | 0.9884 |
| 15% | 1.1176 | 1.0941 | 1.0706 | 1.0471 | 1.0235 | 1.0000 |

## THE DRYING PROCESS

### Psychrometrics

A knowledge of the drying process requires a knowledge of psychrometrics as well as a knowledge of the concept of sensitive heating, adiabatic saturation, and equilibrium moisture content.

Normal atmospheric air is a mixture of dry air and water vapour. A psychrometric chart is a graphical representation of the physical and thermal properties of atmospheric air for a particular barometric pressure. Most charts are constructed to be used at a barometric pressure of 101.325 kPa (normal atmospheric pressure at sea level). The psychrometric chart has five sets of skeleton lines as is shown on Fig. 1.

1. Dry bulb temperature--is the temperature of the air as measured by an ordinary thermometer (represented by vertical line on chart)
2. Wet bulb temperature--is the temperature of the air as measured by an ordinary thermometer whose glass bulb is covered by a wet cloth or gauze (represented by oblique lines at small angle)
3. Dewpoint temperature--is the temperature at which moisture condenses on a surface (represented by horizontal line with figures read from left side)
4. Relative humidity--is the ratio of actual partial pressure of the water vapour to the saturation partial pressure at the same temperature (represented by lines sweeping upward from left side of chart)
5. Specific volume--is the volume occupied by a unit weight of dry air (represented by steep acute angled lines)

Carrier

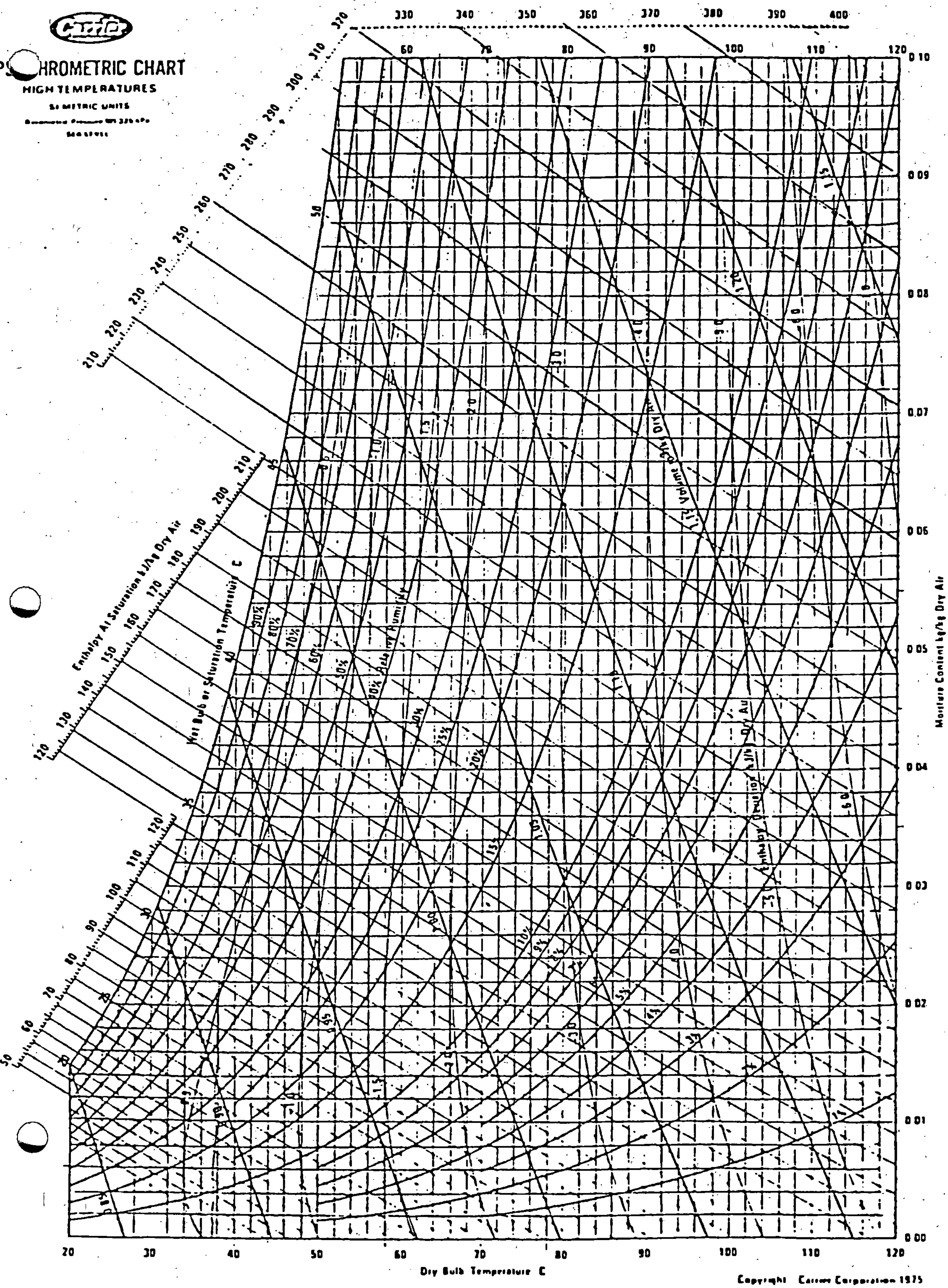
# PSYCHROMETRIC CHART

HIGH TEMPERATURES

SI METRIC UNITS

Barometric Pressure 101.325 kPa

SEA LEVEL



If any two values among the above are known all other values can be obtained. In addition to the five sets of skeleton lines we have the following:

1. Humidity ratio--is the weight of water vapour diffused through or mixed with a unit weight of dry air (read on horizontal line from right-hand side)
2. Enthalpy of an air-water mixture--is equal to enthalpy of the air plus enthalpy of the water vapour (read from wet bulb lines)

The humidity ratio and enthalpy of an air-water mixture are required to determine the size of the heat source.

## Equilibrium Moisture Content

Each grain variety displays a characteristic water vapour pressure at a given temperature and moisture content. When the vapour pressure of the water held by a product is equal to the water vapour pressure of the surrounding air, the moisture content of the product is the equilibrium moisture content (e.m.c.).

When the vapour pressure is less in the air than in the grain there is a drying effect and the grain gives up moisture until the air and grain pressures are in equilibrium. Similarly when the vapour pressure of the grain is less in the grain that in the air the grain takes up moisture from the air and becomes wetter. This process continues until both pressures are the same.

The e.m.c. is important as drying may be carried out unnecessarily resulting in a reduction in the capacity of a given drying system, a higher cost of drying, and an economic loss.

The difference in e.m.c. values for a particular product are often due to variations in measuring techniques and grain varieties. An increase in temperature decreases the e.m.c. There is also a difference in adsorption and desorption e.m.c. curves (desorption values are higher) and unless these are all stated an e.m.c. curve is rather empirical. Several models have been proposed to calculate e.m.c. curves for cereal grains and are well defined by Brooker, Bakker-Arkema and Hall (1974); Chen and Clayton (1970); and others too numerous to mention. A synthesis of some of the well-documented e.m.c. data has been made at the Tropical Products Institute in the U.K. Since most e.m.c. curves deal with isolated temperatures or relative humidity, a mathematical formula such as the one following for a desorption curve at 20°C, is often more useful in dryer design.

$$Y = \exp(k - m \exp(-nx)) \tag{2}$$

where $k,m,n$ = constants given in Table 4

$x$ = m.c. on dry basis as decimal fraction

$y$ = relative humidity

## Heat and Mass Transfer

In drying, two processes are involved--sensible heating and evaporative cooling/adiabatic saturation. In sensible heating all the heat added goes into changing the temperature of the air and no heat goes into changing the air-vapour mixture.

In adiabatic saturation/evaporative cooling we get a cooling of the air as sensible heat is used as latent heat of vaporization to evaporate the moisture at the grain kernel surface. This moisture is removed by the moving air. This transfer is due to differences in vapour pressure between the grain and the drying air. The vapour pressure in the grain depends on grain moisture content and temperature.

TABLE 4 Constants to Calculate e.m.c.

| Material | k | m | n |
|---|---|---|---|
| Barley | -0.05 | -7.17 | 19.90 |
| Buckwheat | -0.02 | 8.28 | 19.44 |
| Corn, shelled,YD | 0.06 | 4.60 | 14.10 |
| Corn, shelled, WD | 0.08 | 4.55 | 13.82 |
| Corn, shelled, POP | 0.00 | 6.79 | 18.63 |
| Flaxseed | -0.09 | 9.93 | 36.90 |
| Oats | -0.02 | 6.08 | 18.81 |
| Rice, rough | 0.03 | 5.37 | 17.10 |
| Rice, undermilled | 0.08 | 5.13 | 14.72 |
| Rice, polished | 0.10 | 5.49 | 14.19 |
| Rye | -0.07 | 8.98 | 21.75 |
| Sorghum | -0.05 | 8.82 | 21.58 |
| Wheat, white | -0.08 | 10.78 | 23.98 |
| Wheat, durum | -0.08 | 12.43 | 25.87 |
| Wheat, soft red winter | -0.07 | 9.94 | 23.07 |
| Wheat, hard red winter | -0.04 | 6.26 | 18.09 |
| Wheat, hard red spring | -0.07 | 9.75 | 23.18 |

In effect then, one has simultaneous heat and mass transfer in the drying process. Heat transfer in the drying operation will occur through the flow of heat as a result of convection, conduction or radiation or, in some cases, as a result of a combination of any of these effects.

Mass transfer on the other hand, depends on two mechanisms: the movement of moisture internally within the product which is a function of its internal physical nature and its moisture content; and the movement of water vapour from the surface as a result of external conditions of temperature, air humidity and flow, area of exposed surface, and air pressures. In a drying operation either of these mechanisms may be a limiting factor on the rate of drying although they are proceeding simultaneously throughout the drying cycle.

The two major periods of drying are the constant rate period and the falling rate period. In the constant rate period, evaporation is taking place from the surface of the product as long as it is independent of internal mechanisms within the product. The magnitude of the rate of drying during this period depends on three externally operating factors, namely: the heat or mass-transfer coefficient, the area of solid exposed to the drying medium and the difference between the temperature and humidity of the drying medium and that of the product surface.

The point marking the end of the constant rate period and the start of the falling rate period occurs when the rate of moisture diffusion within the product decreases below that necessary to replenish the moisure at the surface. At this point the rate of drying will be a function of the rate at which moisture or moisture vapour can move physically by diffusion and capillary flow from within the product to its surface which decreases as moisture content falls.

The falling rate period could be considerably longer than the constant drying period and depends upon several factors such as material thickness, bed depth, air temperature, air humidity, etc.

## MOISTURE CONTENT

### Moisture Content Expression

At this point in time it might be useful to indicate the two methods of expressing moisture content (m.c.). The m.c. on a wet basis (which is used throughout this text) is calculated by dividing the weight of the water in the product by the total weight. The per cent moisture on a dry basis is calculated by dividing the weight of the water by the weight of dry matter.

$$\text{Thus } M_W = \frac{100W_W}{W_W + W_D} \qquad (3)$$

$$\text{and } M_D = \frac{100W_W}{W_D} \qquad (4)$$

where $W_W$ = weight of water; $W_D$ = weight of dry matter

The two expressions are related:

$$M_D = \frac{100M_W}{100 - M_W} \qquad (5)$$

$$M_W = \frac{100M_D}{100 + M_D} \qquad (6)$$

### Moisture Content Determination

Methods of m.c. determination and some major considerations to be given in using a particular method have been given elsewhere (Muir, 1971; Howard-Hunt and Pixton, 1974) and will be treated lightly here.

Basically m.c. determination is done by either a direct or indirect method. One direct method involves heating a quantity of cereal grain at a certain temperature (ASAE, 1979) given in Table 5. ~~oven~~ for a certain time

A minimum of 15g is placed in two or more tared moisture dishes (as defined by ASAE standard S352). The weight of the dishes is obtained. When the end of the heating period is reached the dishes are covered and placed in a dessicator containing a suitable dessicant. When the dishes reach room temperature, they are weighed again and the m.c. calculated using equation (3) or (4).

TABLE 5 Oven Temperature and Heating Period for Moisture Content Determinations

| Seed | Oven Temperature, ± 1°C | Heating Time hr. | min. |
|---|---|---|---|
| Barley | 130 | 20 | 0 |
| Beans, edible | 103 | 72 | 0 |
| Corn | 103 | 72 | 0 |
| Flax | 103 | 4 | 0 |
| Mustard | 130 | 4 | 0 |
| Oats | 130 | 22 | 0 |
| Rape | 130 | 4 | 0 |
| Rye | 130 | 16 | 0 |
| Safflower | 130 | 3 | 0 |
| Sorghum | 130 | 18 | 0 |
| Sunflower | 130 | 1 | 0 |
| Wheat | 130 | 19 | 0 |

Indirect methods involve the use of moisture meters, hygrometer probes, etc. The principle involved is either capacitance, resistance, or conductivity of the grain. Indirect methods only give approximate results but because of the speed with which m.c. readings can be obtained, I would recommend them for drying trials provided that the machine in question has been proven reliable. Although not necessarily endorsed by either IDRC or myself, the CAE 919 moisture meter is used in grain buying and selling by the U.S., Canada, Mexico, and Britain.

## DESIGN OF A DRYER

### Criteria for Dryer Design

When designing a crop dryer, the following criteria should be considered:

1. Quantity and nature of crop to be dried. The quantity is generally associated with the size of the farmer's harvest.
2. Time available to dry a particular batch. If there is an indication of how long the product will store without a loss in quality this can serve as an index of the maximum time available to dry a batch.
3. Consumer requirements. The taste, odour, colour or general appearance of the dried product has to be acceptable for its end use, ~~of~~ ~~a~~ change in the drying process may be ~~process is~~ required. The maximum temperatures during drying recommended to maintain product quality for the different end uses varies from 35 to 75°C.
4. Initial moisture content. Grains at harvest can have a moisture content of 20-30 per cent; fruits and vegetables can be as high as 90 per cent.
5. Final moisture content. The maximum allowable moisture content for storage of different products was given in Table 1. Since storage containers do not always have homogeneous product temperatures throughout, moisture can be translocated

due to temperature variations. Thus a grain that is dry at one temperature may be unsafe for storage at a selected lower temperature. The final moisture content should be obtained with these points in mind.

6. Adequate materials and labour for dryer construction. Ideally a dryer should be made of local materials and be simple enough so that it can be constructed by local artisans.
7. Adequate labour/technology to maintain and operate the dryer.
8. The dryer must be easy to load and unload.
9. The dryer should be economically feasible. This generally means designing a dryer that can be used to dry crops with various harvest dates to allow the dryer to be operated on a year-round basis.
10. Rainfall, air temperature, relative humidity, wind velocity, and solar radiation The amount of rainfall as well as its periodicity should be known. If adequate wind does not exist, some means of forced convection will have to be set up. Air temperatures, relative humidity and solar radiation are generally within a range that allow for adequate solar drying with suitable conditions. Under inadequate conditions, solar drying alone may not be applicable and hybrid systems may have to be used.
11. The dryer should be socially acceptable.
12. The dryer should be technically sound. The dryer should be capable of drying the crop under imposed condtions to obtain a product of a quality acceptable to the target population.

## Dryer Types

Basically there are three types of solar dryers--direct, indirect and combined.

1. Direct dryers. The product is heated by direct solar radiation. The moisture in the grain is evaporated and removed by moving air. Since temperature control in drying using this type of dryer is difficult, a product can be dried too quickly giving "case-hardening" or at too high a temperature resulting in a poor quality product.
2. Indirect dryers. The product is dried by moving air heated outside the drying chamber.
3. Combined dryers. The product is dried both by direct radiation and by heated moving air.

## Design of the drying chamber

1. Dryer bed size. The dryer bed size should correspond to the size of batch to be dried. Knowing the weight of grain to be dried, one can calculated the volume in a batch by knowing the bulk density. The following values for bulk density are given as ASAE standard D241.2 in kg/m$^3$ (ASAE, 1979).

TABLE 6 Bulk Density of Some Selected Grains

| Grain | Density kg/m$^3$ | Grain | Density kg/m$^3$ |
|---|---|---|---|
| Barley | 615 | Millet | 641 |
| Shelled corn | 718 | Oats | 415 |
| Husked corn | 448 | Rough rice | 577 |
| Cowpeas | 769 | Sesame | 589 |
| Sorghum | 713 | Wheat | 769 |

In initial drying tests, a drying bed thickness of 10 cm is often a suitable starting point.

2. Drying time. Drying time is determined primarily by the length of time a product can be stored in its undried state. It may extend over a period of several days or weeks. Table 8 gives the hours between sunrise and sunset and may be used to calculate approximately the number of days needed to dry a batch. If more than one day is required to dry a batch it should be remembered that some rewetting of the grain will occur when the air temperature drops and the relative humidity increases during the night.

TABLE 7 Calculated Hours Between Sunrise and Sunset

| | Latitude N | | | |
|---|---|---|---|---|
| | 10 | 20 | 30 | 40 |
| January 15 | 11.5 | 10.9 | 10.3 | 9.5 |
| February 15 | 11.7 | 11.4 | 11.0 | 10.5 |
| March 15 | 11.9 | 11.9 | 11.8 | 11.7 |
| April 15 | 12.2 | 12.5 | 12.7 | 13.1 |
| May 15 | 12.5 | 12.9 | 13.5 | 14.2 |
| June 15 | 12.6 | 13.2 | 13.9 | 14.8 |
| July 15 | 12.5 | 13.1 | 13.8 | 14.6 |
| August 15 | 12.3 | 12.7 | 13.1 | 13.6 |
| September 15 | 12.1 | 12.2 | 12.2 | 12.3 |
| October 15 | 11.8 | 11.6 | 11.4 | 11.0 |
| November 15 | 11.5 | 11.0 | 10.5 | 9.8 |
| December 15 | 11.4 | 10.8 | 10.1 | 9.2 |

3. Amount of moisture to be removed. Knowing the quantity of grain to be dried, the m.c. of the grain before drying, and the anticipated m.c. after drying, the amount of moisture to be removed during drying can be obtained by:

$$M_W = \frac{W_i(M_i - M_f)}{(100 - M_f)} \tag{7}$$

where $M_W$ = amount of water to be removed
$W_i$ = initial weight of grain to be dried
$M_i$ = initial m.c.
$M_f$ = final m.c.

4. Heat required to remove water from grain. The heat required to remove water from the grain is given by:

$$q_W = M_W L \tag{8}$$

where L = latent heat of vaporization

The value of L changes throughout the drying process. The value should be based on an estimate of mean grain moisture and mean temperature in the drying zone.

It has been suggested that since the grain does not behave as free water at 30°C the theoretical value of L should be 2.8 mJ/kg. (Exell, 1980)

5. Weight of air needed for drying. The weight of air needed for drying can be obtained from:

$$M_a = \frac{M_W}{H.R._f - H.R._i} \tag{9}$$

where $M_a$ = quantity of air needed for drying
$H.R._f$ = humidity ratio of air leaving dryer (which must be estimated)
$H.R._i$ = humidity ratio of air entering dryer

Alternately we could use an energy balance equation:

$$q_w = M_a C_p (T_f - T_i) \tag{10}$$

where $C_p$ = specific heat capacity of the air
$T_i$ = initial temperature of the air
$T_f$ = final temperature of the air.

In the above equation $T_f$ is ordinarily unknown. It can be obtained through use of psychrometric charts.

6. Volume of air required for drying. By rewriting the ideal gas law one obtains:

$$V = M_a RT/P \tag{11}$$

where R = a constant 0.091 kPa $m^3$/kgK
P = pressure
T = air temperature

7. Required air flow per unit time. The required air flow is obtained by dividing V by the product of the number of minutes of drying time and the volume of the drying bed. The resulting flow rate can then be expressed in $m^3$ of air per minute per $m^3$ of grain. For grains, the bed floor must be such that it will hold the grain to be dried but at the same time offer the least resistance to air flow.

8. The pressure difference across the drying bed. The pressure difference across the drying bed can be obtained from Exell (1980):

$$P_d = (H_1 + H_2)(\rho - \rho') \tag{12}$$

where $H_1$ = height from heat source to bottom of drying bed
$H_2$ = height from top of drying bed to top of chimney
$\rho$ = density of ambient air
$\rho'$ = density of air inside dryer
$P_d$ = pressure difference

9. Velocity of air through the bed. For small pressure gradient (under laminar/flow)

$$V = k\ dP/dx \tag{13}$$

where V = velocity of the air entering and emerging from the bed

k = a constant = 0.03 $m^2$/Pa min for rough rice (Exell, 1980)

Thus the gradient in the bed can be given as dP/x where x is the bed thickness. Based on the above the velocity can be calculated and one can determine if a fan is required to move the air or if wind velocities are adequate.

10. Dryer efficiency. The amount of heat energy that must be supplied per unit time to heat up the drying air is given by:

$$\bar{q}_s = \frac{M_a(h_f - h_i)}{tv_s} \tag{14}$$

where $M_a$ = total amount of air needed for drying

$h_f$ = enthalpy of air after heating

$h_i$ = enthalpy of ambient air

t = drying time

$v_s$ = specific volume of air at initial conditions.

The drying efficiency would than be:

$$e = \bar{q}_w / \bar{q}_s \times 100 \tag{15}$$

11. Average temperature in a drying bed. It has been illustrated that upon stirring of a grain bed the final temperature can be calculated as a weighted mean. (Muir, Yaciuk, and Sinha, 1977) Consider the product in the bed to be divided into a series of horizontal spatial elements of thickness $\Delta$ x each at temperature $T_i$.

Upon adequate mixing of the grain the average product temperature is given by:

$$\bar{T} = \Sigma\ V_i \rho_i c_i T_i \Big/ \Sigma\ V_i \rho_i c_i \tag{16}$$

where $V_i$ = volume of grain in element i.

$\rho_i$ = mean density of grain in element i.

$c_i$ = mean specific heat of grain in element i.

If specific heat and density of the product in each element are uniform, equation (16) reduces to:

$$\bar{T} = \Sigma\ V_i T_i \Big/ \Sigma\ V_i \tag{17}$$

12. Average product moisture in a drying bed. The average product moisture is given as a weighted mean and is given by:

$$\bar{M} = \Sigma\ V_i M_i \Big/ \Sigma\ V_i \tag{18}$$

## Design of the Heat Source

If measurement of solar radiation is possible with suitable instrumentation this section would be only of minor importance.

The method to calculate direct solar radiation is that used by Yaciuk (1973). It It is a relatively simple method which lends itself to computer calculations in determining heat transfer rates using finite difference techniques, and has been found adequate in simulating temperatures in grain storage systems (Yaciuk, Muir and Sinha, 1975).

1. Solar altitude and solar zenith angles. The angle the sun makes with the horizon is known as the solar altitude (the intensity of the solar radiation received on earth's horizontal surface is directly proportional to the sine of the solar altitude.)

   Solar altitude is a function of latitude ($\phi$), hour of day (h), and declination angle ($\delta$). The declination angle is the angular distance of the sun north (-) or south (-) of the celestial equator. The zenith angle ($\zeta$) is equal to $\pi/2$ radians the altitude angle and is given by: (Threkeld, 1970)
   minus

$$\zeta = \cos^{-1}(\sin\phi \sin\delta + \cos\phi \cos\delta \cos h) \qquad (19)$$

2. Azimuth angle. The sun's azimuth angle (the angle in the horizontal plane measured from north to the horizontal projection of the sun's rays) is given by:

$$\gamma = \sin^{-1}(\cos\delta \sin h/\sin\zeta) \qquad (20)$$

   The latitude of several locations in the world can be obtained from the ASHRAE guide (ASHRAE, 1972).

3. Hour of sunset. Since the earth rotates on its axis every 24h then each degree of rotation represents a time of 4 min. At solar noon $h = 0$ and $\zeta = \phi - \delta$. Then at sunset $\zeta = \pi/2$. Therefore, from equation (19) the solar hour angle at sunset is:

$$H^{+} = \cos^{-1}(-\tan\phi \tan\delta) \qquad (21)$$

   Since the solar hour angle is symmetrical about solar noon, the sunrise solar angle ($H^{-}$) would be $-H^{+}$. For latitudes greater than 66.5$^{o}$N the possibility of a day or night longer than 24 hours exists. Equation (21) can only be applied when $|\phi|<\pi/2 - \delta$ since $\cos^{-1}|\tan\phi \tan\delta|>1$ is undefined.

4. Radius Vector. The radius vector is the ratio of the distance from the centre of the earth to the sun to the length of the semi-major axis of the earth's surface and can be calculated by: (McCullough and Porter, 1971)

$$R = \{1/(1 + 0.0335 \cos(2\pi\chi/365))\} \qquad (22)$$

   where $\chi$ = the day of the year.

   The radius vector can be assumed constant for any one day.

5. Declination angle. McCullough and Porter (1971) suggest the following equation to calculate the declination angle:

$$\delta = \sin^{-1}\left[0.3978 \sin\{2\pi/365\ (\chi - 80) + 0.0335\ (\sin 2\pi\chi/365 - \sin 160\pi/365)\}\right] \qquad (23)$$

Alternatively $\delta$ can be calculated in degrees from: (Lokmanhekim, 1971)

$$\delta = 0.302 - 22.93\cos(w'\chi) - 0.229\cos(2w'\chi) - 0.243\cos(3w'\chi) + 3.851\sin(w'\chi) + 0.002\sin(2w'\chi) - 0.055\sin(3w'\chi) \quad (24)$$

where $w' = 2\pi/366$

The declination angle can be assumed equal throughout one day.

6. Albedo. Albedo is the percentage of short-wave radiation incident on the earth's surface that is reflected by the earth's surface. Albedo ($a_\ell$) can be approximated by: (Brunt, 1939)

$$a_\ell = 0.70C_c + 0.17(100 - C_c) \quad (25)$$

where $C_c$ = cloud cover, per cent.

7. Instantaneous flux at outer atmosphere. The instantaneous flux of solar radiation at the top of the atmosphere is:

$$I_o = \frac{S}{R^2}\cos\zeta \quad (26)$$

where $I_o$ = heat flux at top of atmosphere
$S$ = solar constant

An exact solution is available for integration of equation (26)

8. Instantaneous flux at the earth's surface. Kreith (1969) suggests that the instantaneous flux at the earth's surface is:

$$I_e = \frac{S}{R^2}\cos\zeta\,(1 - a_\ell)^{\sec\zeta} \quad (27)$$

where $I_e$ = heat flux at earth's surface

9. Instantaneous flux on a tilted surface. For a surface tilted $\psi$ degrees from the horizontal and whose normal faces $\alpha$ degrees westward, the radiation intensity can be divided into perpendicular and parallel components (Kreith, 1969). The ratio of the intensity incident on the tilted surface ($I_v$) to the intensity incident on a horizontal surface ($I_e$) is given by:

$$I_v/I_e = \cos|\zeta - \psi| - \sin\zeta\sin\psi + \sin\zeta\sin\psi\cos|\gamma - \alpha| \quad (28)$$

where $I_v$ = heat flux on surface tilted $\psi$ degrees from the horizontal.

Thus equation (28) becomes:

$$I_v = I_e\,(\cos|\zeta - \psi| - \sin\zeta\sin\psi + \sin\zeta\sin\psi\cos|\gamma - \alpha|) \quad (29)$$

To the best of my knowledge, no exact solutions exist for equation (27) or equation (29). Integration using the trapazoidal rule with increments of four minutes (one degree) has been found satisfactory (Yaciuk, 1973).

## Considerations in Collector Design

1. Need for solar collector covers. Solar collector covers serve three purposes:
   a) They reduce convection heat transfer by shielding the absorber from the wind
   b) They admit shortwave radiation to the absorber, and
   c) They prevent escape of longwave radiation from the collector.

2. Types of material for collector covers. Wien's displacement law states that the wavelength for which radiation has the greatest intensity is proportional to the absolute temperature of the black body. Based on this law, maxium intensity of solar radiation is around 0.5 $\mu$ while radiation emitted by the earth is around 11 $\mu$ (Yaciuk, 1973). The "greenhouse effect" is based on this principle. The type of material best suited for covering a collector is one that has a shortwave transmittance of 1.0 and a longwave transmittance of 0. This ensures that all solar energy received goes through the covering and that there is no heat loss due to outward radiation heat transfer from the collector. In reality this is not possible, and one usually settles for something less.

   Other desirable properties of cover materials include: (North Dakota State U., 1980)
   a) resistance to static charges
   b) high impact strength
   c) resistance to wind damage
   d) resistance to deterioration by UV light
   e) resistance to deterioration at high temperatures
   f) low coefficient of thermal expansion
   g) light weight
   h) economical
   i) easy to install and maintain
   j) low coefficient of conduction heat transfer.

3. Properties of good absorbers.
   a) Absorbs most of the shortwave solar radiation. The shortwave absorbance should be near unity.
   b) Heat losses to the collector's surroundings are minimal--the longwave emittance should be near zero and insultation of the collector should be adequate
   c) High transfer rate of absorbed energy to the moving air.

4. Collector efficiency. Collectors are designed with a particular tilt-angle and orientation. Collector efficiency therefore varies throughout the day. Efficiciency usually increases with collector cost. More insulation of the collector, better absorber and cover materials may increase efficiency but the system quickly becomes too costly when drying low-cost items such as cereal grains.

## Considerations in Drying Chamber Design

1. Indirect dryers.
   a) An increase in the drying air temperature increases the drying rate. Increasing the air temperature to too high a level can result in case-hardening, excessive shrinkage, etc of the product.
   b) At high temperatures, the bottom layer of a fixed bed tends to overdry and may give an inferior product. Even though the average temperature and moisture content after mixing is acceptable, individual particles in the bed to be dried may be damaged. This often shows up as a processing loss.
   c) An increase in the airflow rate increases the drying rate. If the drying time needs to be shortened, the better alternative would be an increased airflow rather than increased temperature.
   d) For grains, an increase in bed depth increases the moisture gradient through

the bed even though the average moisture content may not be that greatly affected under certain drying conditions.

e) Adequate chamber wall should be provided to keep heat losses through the wall to a minimum.

2. Direct dryers. The altitude angle of the sun plays an important role since the dryer must be designed in such a way that the dryer receives the desired amount of solar energy. From equation (19) we get the following altitude angles at latitude 10°N:

TABLE 8 Altitude Angles at Latitude 10°N

| | Noon | ±1 hr. | ±2 hrs. | ±3 hrs. | ±4 hrs. |
|---|---|---|---|---|---|
| January 15 | 58.7 | 55.4 | 47.0 | 35.9 | 23.3 |
| February 15 | 67.0 | 62.6 | 52.4 | 39.8 | 26.2 |
| March 15 | 77.6 | 70.6 | 57.7 | 43.5 | 29.0 |
| April 15 | 89.4 | 75.2 | 60.4 | 45.7 | 30.9 |
| May 15 | 81.5 | 73.2 | 59.8 | 45.7 | 31.5 |
| June 15 | 76.7 | 70.5 | 58.4 | 45.1 | 31.4 |
| July 15 | 78.2 | 71.4 | 58.9 | 45.3 | 31.4 |
| August 15 | 85.8 | 74.7 | 60.4 | 44.9 | 31.3 |
| September 15 | 83.0 | 73.5 | 59.4 | 44.8 | 30.1 |
| October 15 | 71.6 | 66.3 | 54.9 | 41.6 | 27.5 |
| November 15 | 61.9 | 58.2 | 49.2 | 37.4 | 24.5 |
| December 15 | 56.9 | 53.8 | 45.8 | 34.9 | 22.6 |

Using equations from the section on design of the heat source, one can determine the quantity of solar energy between two times symmetrical about noon and then design the dryer in such a way that the drying bed receives the required solar energy. For example, if the bed-edge were 10 cm away from the drying chamber wall, the bed surface could not be placed more than 4.3 cm below the top of the chamber wall to receive solar energy on January 15 between 0800 and 1600 hours.

Having the dryer bed adjacent to the chamber wall results in uneven drying of the product, since there will always be an area not receiving any sun, unless the bed surface is flush with the top of the drying chamber.

## EVALUATION OF THE DRYER

When the prototype dryer has been built, in order to assess it both technically and economically, the following data should be obtained:

1. Product
   a) initial batch weight
   b) final batch weight
   c) initial moisture content

d) final moisture content
e) price for unit weight of undried product
f) price of unit weight of dried product

2. Drying process on an hourly basis (for indirect drying)
   a) ambient air--wet bulb
   b) ambient air--dry bulb
   c) drying air--wet bulb
   d) drying air--dry bulb
   e) air velocity of drying air at inlet and outlet
   f) exhaust air--wet bulb
   g) exhaust air--dry bulb
   h) air velocity above bed
   i) moisture reduction in product (kg of $H_2O$/hr)
   j) mean drying rate (per cent moisture content/hr)
   k) quantity of heat provided

3. At end of drying process
   a) drying time
   b) moisture reduction (kg of $H_2O$/hr)
   c) mean drying rate (per cent moisture content/hr)

4. Economic evaluation
   a) dryer cost
   b) life of the dryer
   c) fixed costs--depreciation
   d) --interest on investments
   d) variable costs--repairs and maintenance
      --labour
      --miscellaneous expenses
   e) drying cost per unit weight of product
   f) break-even point analysis--fixed costs/(income from sale of product - variable cost)
   g) return on investment--net income/total costs
   h) pay-back period--capital investment/(total net income per year + depreciation cost)

## PRACTICAL APPLICATION

The publication Food Systems describes the drying projects funded by IDRC (Forrest and colleagues, 1980). Some of these will be discussed by my colleagues with specific reference to:

1. The various times of the year when the crop is harvested
2. The average moisture content of the harvested crop
3. The amount harvested per day
4. The fraction of the daily harvest which will be preserved through dehydration
5. Storage conditions of dried products
6. The range and average for climatic conditions (solar radiation intensities, windspeeds, rainfall, ambient air temperatures and relative humidities) during the harvest period
7. The normal time after the harvest by which the crop must be dehydrated to prevent spoilage (this is generally well-known in traditional societies)
8. The equilibrium moisture content for the particular crop varieties under consideration

9. Existing sun-drying operations for the crop, their problems and advantages, and the traditional experience gained through the use of these techniques
10. Other possible crops that need to be dried during the same time and at other times of the year
11. The cost differential between fresh and preserved product, in order to determine the economic viability of dehydration as an option.
12. The price differential (if any) between a unit amount of sun-dried or artificially dried product in the prospective market where the dehydrated material is to be sold
13. An economic cost-benefit study on the drying system
14. Data, from a drying trial, collected relating to heat and mass transfer.

A comprehensive review of solar dryers has been done by the Brace Research Institute Case studies on several different dryers have been done and may be of interest.

TABLE 9 List of Case Studies on Solar Agricultural Dryers
(Brace Institute, 1975)

| Section | Title of Case Study |
|---|---|
| Natural and Sun-Dryers | Coffee dryers (Colombia)<br>Drying grapes on racks (Australia)<br>Natural vertical dryer (Colombia) |
| Direct Solar Dryers | Solar fruit dryer (Brazil)<br>Solar cabinet dryer (Syria)<br>Solar cabinet dryer (India)<br>See-saw dryer (Ivory Coast)<br>Solar dryer for cereal and grains (Great Britain)<br>Glass-roof solar dryer (Brazil) |
| Mixed Mode Solar Dryers | Solar fruit and vegetable dryer (U.S.A.)<br>Preheated circulation solar dryer (Turkey)<br>Orchard type solar dryer (Turkey)<br>Laboratory type solar dryer(Turkey)<br>Natural convection dryer (Trinidad)<br>Solar wind ventilated dryer (Syria) |
| Indirect Solar Dryers (with forced ventilation) | Solar herbs and flowers dryer (U.S.A.)<br>Batch shallow bed coffee drying bins (Puerto Rico)<br>Solar supplemental heat drying bin (U.S.A.)<br>Large scale solar agricultural dryer (Barbados) |

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## REFERENCES


ASAE (1979). Agricultural Engineer's Yearbook. ASAE, St. Joseph. p. 740.

ASHRAE (1972). Handbook of Fundamentals. ASHRAE, New York. p. 688.

Brace Research Institute (1975). A Survey of Solar Agricultural Dryers, Technical Report T99. McGill University, Montreal.

Brooker, D. B., F. W. Bakker-Arkema, and W. Hall (1974). Drying Cereal Grains. AVI, Westport. p. 265.

Brunt, D. B. (1939). Physical and Dynamic Meteorology. University Press, Cambridge. p. 428.

Chen, C. S., and J. T. Clayton (1970). Equilibrium moisture curves for biological materials--the effect of temperature. ASAE paper. pp. 70-283.

Exell, R. H. B. (1980). Basic design theory for a simple dryer. Submitted for publication.

Forrest, R.S., W. Edwardson, S. M. Vogel, and G. Yaciuk (1980). Food Systems. International Development Research Centre, Ottawa.

Hall, D. W. (1970). Handling and Storage of Food Grains in Tropical and Subtropical Areas. Food and Agriculture Organization of the United Nations, Rome. p. 350.

Haward, O., W. Hunt, and S. W. Pixton (1974). Moisture--its significance, behaviour and measurement. In C. M. Christensen, Storage of Cereal Grains and Their Products. AACC, St. Louis. p. 549.

Kreith, F. (1969). Principles of Heat Transfer. International Textbook Company, Scranton. p. 619.

Kreyger, J. (1972). Drying and Storage of Grains, Seeds and Pulses in Temperate Climates. ISVL, Wageningen. p. 333.

Lokmanhekim, M. (Ed.) (1971). Procedure for Determining Heating and Colling Loads for Computerized Energy Calculations. Algorithm for Building Heat Transfer Subroutines. ASHRAE, New York. p. 84.

McCullough, E. C., and W. P. Porter (171). Computing clear day solar radiation spectra for the terrestrial ecological environment. Ecology, 52, 1008-1015.

Muir, W. E. (1971). Temperature and moisture in grain storages. In R. N. Sinha and W. E. Muir (Ed.), Grain Storage Part of a System. AVI, Westport. p.481.

Muir, W. W., G. Yaciuk, and R. N. Sinha (1977). Effects of temperature and insect and mite populations of turning and transferring farm-stored wheat. Canadian Agricultural Engineering, 19, 25-28.

North Dakota State University (1980). Low Temperatures and Solar Grain Drying Handbook. NDSU, Fargo. p. 86.

Sinha, R.N. (1971). Interrelationships of physical, chemical and biological variables in the deterioration of stored grains. In R. N. Sinha and W. E. Muir Grain Storage Part of a System. AVI, Westport.

Taylor, R. W. D. (1975). The Storage of Seeds. Tropical Stored Products Institute Bulletin No. 30. TSPC, London.

Threkeld, J. L. (1970). Thermal Environmental Engineering. Prentice Hall, Toronto p. 495.

Yaciuk, G. (1973). Temperatures in grain storage systems. Unpublished PhD dissertation. p. 171.

Yaciuk, G., W. E. Muir, and R. N. Sinha (1975). A simulation model of temperatures in stored grain. Agricultural Engineering Research, 20, 245-258.